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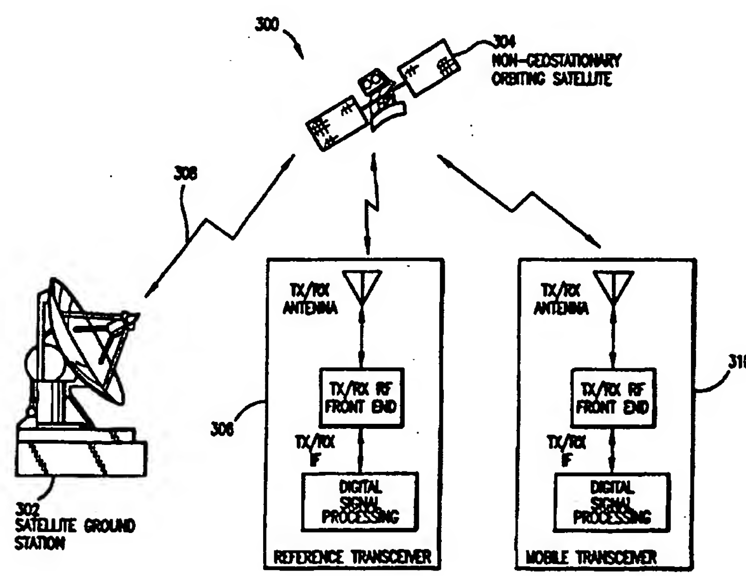
(54) Title: METHOD AND APPARATUS FOR PRECISION GEOLOCATION

(57) Abstract

A method and apparatus for providing an improved satellite-based tracking system use a reference transmitter at a site with a known location to provide an error correction vector, which can be applied to improve the position estimate of transmitter at unknown locations. The technique of determining the position of a transmitter on the ground is known as geolocation. For the purpose of geolocation, a transmitter/receiver (transceiver) is interrogated via a satellite ground station through a satellite transponder in Earth orbit. Upon reception of the transceiver's unique identificataon code broadcast by the satellite, the transceiver will transmit its identification code back to the satellite ground station via the satellite transponder. The round strip response time is used to calculate the range from the satellite to the transceiver. The Doppler shift of the received signal, due to the satellite motion of a satellite in non-geostationary orbit, is used to calculate the angle-of-arrival at the satellite. The range and angle-of-arrival are combined to calculate the position estimate of the location of the transceiver. This geolocation process is repeated for a transceiver at a known reference site and for all mobile and/or fixed transceivers at unknown sites. The position estimate generated for the reference transceiver is compared to the a-prior known position reference transceiver. The difference between the position estimate and the known location of the reference side produces an Error Vector. This Error Vector is then applied to the position estimates of all transceivers at the a-prior unknown positions to provide an improved position estimate.



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METHOD AND APPARATUS FOR PRECISION GEOLOCATION

FIELD OF THE INVENTION

The present invention relates generally to methods and systems for performing geolocation, and more particularly to a method and system for performing global geolocation via a non-geostationary earth orbiting satellite.

BACKGROUND OF THE INVENTION

The ability to locate and track people and devices has numerous law enforcement, commercial and consumer applications. By developing a base technology that can meet the diverse needs of all of these applications, a low unit cost through high volume production can be achieved allowing the affordable fielding of a technology that can drastically lower the costs and raise the effectiveness of military police operations, for example.

One application, for example, consists of monitoring parolees. California has approximately 100,000 parolees (state level - not including probationers) that the state government would like to have tracked. On October 12, 1995 the Governor of California approved Assembly Bill No. 1804, which requires the continuous electronic monitoring and position reporting of parolees, probationers and prisoners. The legislation passed requires a position update once every five minutes or less. It requires a body worn device, severely limiting the choice of operational frequencies. With costs of $21,000 a year for incarceration, en estimated $4000 a year for monitoring is very attractive.

Another example is personal rescue. Today, there is no simple, reliable method of determining the position of a person needing rescue. The example of Captain Scott O-Grady illustrates the fact that a downed pilot is unwilling to transmit

for fear that the transmission will be intercepted and his position compromised. Some, proposals, such as the Combat Survivor and Evader/Locator Program, require that a GPS derived coordinate be encrypted and then transmitted over a secure link This approach requires the bulk, cost, and power demanded by a GPS receiver and the subsequent encryption equipment

In addition, the tracking of people must be performed inside of buildings, outside of buildings, over wide areas, using a low cost communication link and with a long battery life. While the Global Positioning System (GPS) is well suited for navigator and position determination outdoors and over wide areas due to the global nature of the NAVSTAR system, GPS does not meet the indoor requirements due to the inability of the GPS signal to penetrate buildings.

Furthermore, many prior art navigation systems are known, such as the Global Positioning System (GPS), GLONASS, LORAN, OMEGA, TACAN, and the like. While navigation units could be configured to incorporate transmitters to relay position reports, which take advantage of these existing navigation systems, these transmitters would substantially increase the cost, complexity, size, weight, and power consumption of the mobile units. Also, it would make the unit incompatible for operation on a human being. In addition, the above mentioned prior art systems are largely used for out-of-doors military vehicle (ships, tanks, aircraft) navigation functions rather than in-door and personal geolocation functions.

In addition, the prior art systems perform their geolocation functions using two or more transmitter and/or receiver platforms that are located at distant positions. In the case of satellite based prior art systems, at least three and preferably four in-view satellites must be available to the geolocation receiver at all times in order to achieve a position solution. Finally, the use of prior art satellite based systems will not penetrate building structures, thick vegetation, or sheltered areas.

The present invention is therefore directed to the problem of developing a method and apparatus for performing enhanced global geolocation, which does not require large mobile devices or multiple satellites and which will operate indoors and in numerous types of environments.

SUMMARY OF THE INVENTION

The present invention solves this problem by determining an error vector representing a difference between a known location of a fixed reference station and a measured location, and applying that error vector to a measured location of the mobile unit. By so doing, the present invention relies only on a single satellite, does not require GPS based receivers/transmitters, which keeps the size and power small, and can operate at frequencies that penetrate numerous environments, while providing an accurate position measurement.

According to the present invention, a method for locating a mobile unit includes determining the location of a reference unit, calculating an error vector that represents the difference between the actual known position and the measured position, estimating the position of the mobile unit using the same technique used to measure the location of the reference unit, and applying the error vector to the estimate position of the mobile unit to determine the final position of the mobile unit.

According to one advantageous embodiment of the present invention, to determine the location of the reference unit and to estimate the position of the mobile unit, the present invention measures the doppler shift in a signal transmitted from the ground units to a satellite to obtain a first position curve on the surface of the earth on which the ground unit may be located, uses the time of arrival of the signal transmitted from the ground unit to the satellite to determine a second position curve on the surface of the earth on which the ground unit may be located, and determines a point of intersection of the first position curve and the second position curve, which defines an estimate of a location of the ground unit.

According to the present invention, a system for determining with a high degree of accuracy a location of a mobile unit based upon signals transmitted from a low earth orbiting satellite, which is disposed in a known orbit about the earth, the mobile unit being capable of moving selectively throughout a geographical area, includes a command center, a transmitter for transmitting geolocation information and other data from the command center to the mobile unit, a receiver for receiving Doppler frequency shift, time of arrival, and angle of arrival data, and other data from the mobile unit via the low earth orbiting satellite to the command center, and a

measurement/geolocation/service processor residing in the command center. In this case, the processor determines a Doppler frequency shift component of a plurality of geolocation parameters, a time of arrival component of the plurality of geolocation parameters, an angle of arrival component of the plurality of geolocation parameters, and an approximate position of the mobile unit transmitter signal traveling between the mobile unit and the low earth orbiting satellite. The command center includes a receiver for receiving differential data regarding a plurality of fixed reference stations and the approximate position of the mobile unit. The processor determines based upon the approximate position of the mobile unit and known locations of the plurality of fixed reference stations a determined one of said plurality of fixed reference stations that is presently in view of a same satellite as the mobile unit, and combines the approximate position of the mobile unit and the differential data from the determined one differential station to provide an accurate position of the mobile unit. In this case, the processor in the command center calculates an accurate location using a differential technique and the position and other data is transmitted via a terrestrial wireless transmission system or via the Internet data transmission network.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG 1 graphically depicts the LEO satellite global coverage of the LEO satellite constellation used in the present invention.

FIG 2 graphically depicts the LEO satellite beam footprint of the satellite constellation used in the present invention.

FIG 3 shows the geolocation system of the present invention

FIG 4 shows the mobile transceiver unit of the present invention.

FIG 5 illustrates the range measurement technique used in the present invention.

FIG 6 illustrates the Doppler measurement technique used in the present invention.

FIG 7 shows the combined range and Doppler measurement of the present invention.

FIG 8 illustrates the location algorithm for the mobile unit of the present invention.

FIG 9 shows the error correction vector method of the present invention.

FIG 10 shows a map of a typical placement of differential Doppler base stations.

DETAILED DESCRIPTION

A method and an apparatus for providing an improved satellite-based tracking system is described. The method uses a reference transmitter at a site with a known location to provide an error correction vector, which can be applied to improve the position estimate of a transmitter at unknown locations.

The technique of determining the position of a transmitter on the ground is known as geolocation. For the purpose of geolocation, a transmitter/receiver (transceiver) is interrogated via a satellite ground station through a satellite transponder in Earth orbit. Upon reception of the transceiver's unique identification code broadcast by the satellite, the transceiver will transmit its identification code back to the satellite ground station via the satellite transponder. The round trip response time is used to calculate the range from the satellite to the transceiver. The Doppler shift of the received signal, due to the satellite motion of a satellite in non-geostationary orbit, is used to calculate the angle-of-arrival at the satellite. The range and angle-of-arrival are combined to calculate the position estimate of the location of the transceiver. This geolocation process is repeated for a transceiver at a known reference site and for all mobile and/or fixed transceivers at unknown sites. The position estimate generated for the reference transceiver is compared to the a-prior known position reference transceiver. The difference between the position estimate and the known location of the reference site produces an Error Vector. This Error Vector is then applied to the position estimates of all transceivers at the a-prior unknown positions to provide an improved position estimate for those transceivers.

To meet the needs of tracking the movement of military police forces and parolees, the present invention includes a wrist-watch sized transmitter and receiver that can be tracked via a Low Earth Orbiting (LEO) satellite. The present invention

eliminates the bulk, cost and power of previous systems by relying on the satellite to perform the geolocation and not the mobile unit -- one embodiment of which is a wrist-watch transmitter and receiver. Another embodiment of the mobile unit includes a transmitter/receiver in a vehicle. In aircraft applications, the present invention tags the person rather than the downed aircraft, which aids in the rescue of a downed pilot. Finally, the mobile unit is designed to be interrogated even if the person is unconscious, hence the position of the person can be determined independently of the state of the person.

Due to the details of the present invention, the transmitter can be made low power, i.e., less than one watt. Furthermore, the battery life will be in the range of approximately 30 days as a result of the architecture of the system.

The satellite system employed by the present invention is independent of the Global Positioning System (GPS) for determination of position, and provides the military with a positioning capability, as well as a means for reporting position to the command center without broadcasting a position coordinate set. To prevent others from detecting the broadcasts, the present invention employs secure spread spectrum communications.

The present invention inexpensively locates a previously tagged missing person or object. Whenever a user is disabled or injured on a covert mission or otherwise needs to be tracked, the mobile unit of the present invention is interrogated by satellite to determine the user's position. This requires no action by the user. The communication between the satellite and the user's mobile unit is performed using inherently secure spread spectrum communications, thus preventing eavesdroppers from listening. Since the position is not broadcast, there is nothing to listen to. The location determination is performed at the satellite's ground station, which then alerts the rescuers or is monitored for tracking applications.

The following chain of events occur in order to locate a user once a request has been received. First, the customer calls the system of the present invention with a request. The ground station then signals the satellite, which broadcasts the communicator identification code. The mobile unit receives the broadcast and

transmits a response. The satellite retransmits the mobile unit's signal back to the ground station, which then calculates the position.

The downlink to the communicator is in the S-Band (2500 MHZ) and the uplink from the communicator is in the L-Band (1600 MHZ). These frequencies enable the use of very small antennas.

A code division multiple access (CDMA) direct sequence spread spectrum approach is used in the present invention to allow for many simultaneous discrete transmitters. This is important for serving large consumer markets inexpensively and for providing secure transmissions.

The present invention uses the Doppler geolocation technique developed by the U.S. Navy Transit Navigation Satellite System of the 1960's and 1970's. This system was replaced by the NAVSTAR/GPS satellites for navigation. The present invention uses the Doppler technique because it is simple and low cost, while providing satisfactory positional accuracy. To improve the accuracy of this technique, the present invention adds a Differential Doppler technique, which is discussed below.

The Doppler technique relies upon a shift in frequency between the satellite and the mobile unit. As the satellite orbits the earth, the shift of a signal received from a transmitter on the surface of the earth is detected. The Doppler shift resulting from the relative velocity between the satellite and the transmitter represents a surface of a cone that the transmitter must lie upon. The transmitter is assumed to be on the surface of the earth, which eliminates most of the cone's surface as possible points. Consequently, a line of position can be determined from one Doppler measurement, which is the line the cone and the earth intersect.

A short interval later (e.g., one minute) a second Doppler measurement is made, and a second line of position can be determined. The intersection of the two resulting lines of position represents a position estimate for the mobile unit. Since the mobile unit is not moving fast under most circumstances this is sufficient to locate the mobile unit.

In addition, the present invention uses pseudo ranging techniques to determine the position of the mobile unit.

By combining the aforementioned Doppler technique and the ranging technique. the present invention is able to provide an instantaneous fix using only one satellite. Doppler positioning has been superseded by NAVSTAR GPS because of the inability to track quickly moving objects such as aircraft. For the present applications, such as locating personnel, the person is not usually moving quickly, and thus the combined Doppler and pseudo ranging technique will work effectively

To further improve the accuracy, the present invention employs a differential Doppler technique, which relies upon providing a second fixed location communicator to the operational scenario discussed above. The second communicator is placed in a fixed known reference location. As the satellite flies over the operational area, both the unknown communicator and the reference communicator are interrogated. The Doppler measurement of the reference tag provides an error correction vector that can be applied to the position estimate of the unknown tag. Using this Differential Doppler approach, it is estimated that the position uncertainty can be reduced from 1000 meters to 30 meters.

Only a few reference communicators need to be deployed to serve a large area. Since the accuracy of the error corrector vector degrades as the paths of the two signals diverge, the two paths must pass through nearly the same portion of the ionosphere for the technique to be accurate. Fortunately, a narrow angle of divergence at the satellite produces a very large spatial divergence at the surface of the earth. Thus, one fixed reference communicator enables an accurate location radius of hundreds of miles. The above approach will provide location accuracies to within 100 meters.

The present invention minimizes the operational requirements for the transceiver for the mobile unit, thus enabling a wristwatch sized unit. This is possible because the satellite performs the geolocation rather than imposing that requirement (and adding GPS) on the mobile unit.

The satellites used in the present invention are low- or mid-earth orbiting satellites due to the higher elevation angles that are achievable. In addition, less transmitter power is required, and the omni-directional antennas eliminate the need for tracking antennas.

One example of the low earth orbiting satellite-based digital telecommunications system is Globalstar. It will provide telephony and other digital telecommunications services, such as data transmission, paging and facsimile. Globalstar service will be delivered through a 48-satellite constellation at 1419 km altitudes. Globalstar, will begin launching satellites in the second half of 1997 and will commence initial commercial operations in 1998. Globalstar is licensed to operate at L and S bands in the United States using spread spectrum communications. Odyssey is essentially the same as Globalstar, except for the higher altitude of the satellites Its first launch is scheduled for 2000.

FIG 1 shows the low earth orbiting satellite global coverage, and the footprint 200 of a single satellite. The satellite used in the present invention is one of a series of low earth orbiting satellites orbiting the earth. To distinguish satellites from each other, satellites are assigned identification numbers that are unique. The placement of the satellites is such that all points on the earth lie within the coverage area of at least one satellite. In the case of the temperate latitudes, multiple satellites are in view of each point. Each satellite in the constellation can cover a continent-sized portion of the earth's surface as shown in FIG 2, which shows the low earth orbiting satellite beam footprint 200 and the associated spot beams 202.

System Overview

The system which is used for the geolocation functions of the present invention is shown in FIG 3. As can be seen in FIG 3, the system 300 includes a satellite ground station 302, a low earth orbiting satellite 304, a reference transceiver unit 306 and a mobile transceiver unit 310. The two transceivers 306, 310 are identical, except for the fact that the reference transceiver 306 is placed in a known location, whereas the mobile transceiver 310 can be moved to any point on the earth. The system of the present invention permits one or more of each of these elements, e.g., the ground station 302, the reference unit 306 and the mobile unit 310. The satellite ground station gateways 302, which also reside on the surface of the earth, are in data communications with in-view low earth orbiting satellites 304 through RF communications channels 308.

In accordance with the present invention, the number of mobile units 310 is not limited. Consequently, the number of mobile units 310 could be in the millions. The mobile unit 310 is portable, battery powered, consumes relatively low power, and includes a relatively small antenna. In accordance with the present invention, the geolocation system can locate the mobile units 310 anywhere on or near the surface of the earth. The mobile units 310 of the present invention communicate with the satellites 304 at frequencies allocated by the appropriate governmental agencies. These frequencies potentially vary from one country to another, however, these frequencies are known to those of skill in the art, hence it is not necessary to provide them in detail herein.

FIG 2 shows a LEO satellite footprint 200 of the satellite spot beam 202 formed on the surface of the earth. Each spot beam 204-232 is formed by a single satellite as it moves along satellite footprint 200. FIG 1 shows the global coverage of the entire satellite constellation.

Each spot beam 204-232 within the satellite footprint 200 occupies a unique position within the satellite footprint 200, hence these positions can be distinguished from one another by assigning each spot beam 204-232 a unique identification code. Consequently, one can obtain a first cut in locating a particular mobile unit by determining which spot beam the mobile unit lies within. This information defines a position relative to a satellite, whose position is usually known from known orbital calculations and tracking. As is known in the art, by combining a spot beam location 204-232 within a satellite footprint 200 with the satellite's position, one can determine the mobile unit's position on the earth within a large area.

According to the present invention, in addition, the location information determined by the unique spot beam 204-232 can be used to perform ambiguity resolution during a geopositioning measurement such as differential Doppler, wherein there are two positions determined, a real position and an image position, i.e., the math predicts two positions (a real and an imaginary position), only one of which is real, the other is termed an image position. The unique spot beam information can be used to choose the real position.

Mobile Transceiver Unit

FIG 4 shows a block diagram of the mobile unit 310. The mobile unit 310 consists of a receive antenna 402, a receiver 404, a digital signal processor 406, a crystal reference 408, local oscillators 410, a transmitter 412, a power supply/battery 414 and a transmit antenna 416. The receiver 404 receives signals from the satellites in low earth orbit via the receive antenna 402. The receiver 404 couples these signals to the digital signal processor 406, which converts the received electromagnetic energy to data and performs all data demodulation and processing. The digital signal processor 406 also performs all of the mobile unit 310 control and status functions and controls all receive parameters such as frequency, timing, Doppler tracking and the like. The digital signal processor 406 is also coupled to the transmitter 412 and converts the data to electromagnetic energy and performs all modulation that is used to transmit signals to the satellite in low earth orbit via the transmit antenna 416. The digital signal processor 406 also controls all transmit parameters such as frequency, timing, and the like. The local oscillators 410 provide the basic frequencies required to receive and transmit the data and are controlled by a very stable crystal reference 408.

Time of Arrival Calculation

Referring to FIG 5, a range sphere 501 represents the time of arrival of the transmitter's 310 signal at the satellite 304. Since electromagnetic signals propagate at a constant velocity equal to the speed of light, a given propagation duration dictates that the source of the signal must lie on the surface of a sphere having a radius equal to the propagation duration times the speed of light and centered at the point where the signal is received. In the present invention, the source of the electromagnetic signal may be the mobile unit 310 located on the surface 503 of the earth and the signal may be received at the satellite 304 orbiting the earth. Thus, a time of arrival circle represents the intersection of a sphere centered at the satellite 304 and having a radius equivalent to the speed of light times the propagation duration with the earth's surface. This is shown in FIG 5 where the time of arrival circle 501 determines the range between the satellite 304 and the mobile unit 310.

In general the coordinates of a point in space can be determined by making a minimum of three range measurements between that point and three known points. Each range measurement describes a hemisphere around a known point (or more generally a complete sphere). When only one measurement is made, the mobile unit 310 can be located anywhere on the surface of the hemisphere 501 (or sphere) with the radius equal to the range 502 and the satellite location at the center of the hemisphere 501 (or sphere). When range measurements are made from two known points, the mobile unit can lie anywhere on the line of intersection 509 between the two hemispheres (or spheres), and when range measurements are made from three non-coplanar known points, the three hemispheres (or spheres) intersect at a unique point corresponding to the position of the mobile unit 310. This provides three equations with three unknowns. If the earth is taken as one of the spheres, then only two measurements are required and the location of the mobile unit is at the intersection of the surface of the earth and the two range measurement hemispheres (or spheres). This is shown in FIG 5. A given propagation duration intersection with the earth's surface is a circle centered at a point on the satellite ground track where the satellite nadir direction intersects the surface of the earth. Longer propagation durations result in circles having larger radii. The time of arrival curve determined represents the circle that describes the propagation duration indicated in the measurement record.

Actually, two separate range measurements are shown in FIG 5, which can be used to obtain an estimate of the location of the mobile unit 310, however, only one range measurement is needed in the geolocation method of the present invention. The range sphere 501 intersects the surface of the Earth 503 and produces a circular line of position 505, 507. A transmitter 310 on the ground must lie on this circular line of position 505, 507 in order to produce the time of arrival measured at the satellite. For the two range measurement case, the intersection 509 of the two lines of position 505, 507 represents the position measurement.

According to the present invention, the time of arrival of the signal at the satellite is measured by sending a signal from a satellite ground station 302, through the satellite transponder 304, to the transmitter 310 instructing the transmitter 310 to

reply with an acknowledgment (an interrogation). The total time delay measured includes the transmit time from the ground station 302 to the satellite 304. the transponder delay time, and the transmit time from the satellite 304 to the transceiver 310 on the ground. The transmit time from the ground station 302 to the satellite 304 can be removed since both the positions of the satellite 304 and the ground station 302 are known. Likewise the transponder time delay is known through ranging calibration measurements. Thus, the time of arrival of the signal at the satellite 304 can be determined.

Angle of Arrival Calculation Using Doppler Shift

FIG 6 shows a portion of the geolocation process according to the present invention using a single satellite 304 The geolocation system of the present invention activates the geolocation process with respect to a specific mobile unit 310 when a measurement record relating to that mobile unit 310 is received. The geolocation process determines a frequency of arrival parabola to fit the Doppler component data contained in the measurement record. This frequency of arrival parabola or line of position 616 is shown in FIG 6. Since the satellite 304 is orbiting the earth and the mobile units 310 are located on the surface 503 of the earth, the direction with which a satellite 304 moves with respect to a mobile unit 310 continually changes. Since this direction continually changes but the satellite orbital velocity remains relatively constant, the component of satellite velocity in a radial direction toward the mobile unit 310 continually changes. At any instant of time, the satellite 304 has a particular velocity or range rate vector 614. As a result of the continual velocity change, the Doppler component continually changes relative to a stationary mobile unit 310 on the surface of the earth. The Doppler shift of the signal is represented by a cone 610 centered on the satellite velocity vector 614 with the degree of Doppler shift being proportional to the angle off the velocity vector 614. A given Doppler component could be reported from any point located on the cone 610 centered around the satellite velocity vector 614.

When a Doppler measurement is made, the position of the mobile unit 310 must lie somewhere on the surface of the Doppler cone 610. If it is assumed that the

mobile unit 310 is located on the surface of a spherical earth. the mobile unit 310 will then lie somewhere on the line of intersection of the Doppler cone 614 and the earth 503. This line of intersection (known as line of position 616) is typically a parabola. A given Doppler component could be reported from any point located on the parabola centered about the ground track of the satellite 304 and extending away from the satellite 304. Higher Doppler rates result in narrower parabolas while at zero Doppler, which occurs when a satellite 304 is directly overhead, the Doppler curve has an infinite width and is essentially a straight line perpendicular to the satellite ground track. The frequency of arrival curve represents the curve that describes the Doppler component indicated in the measurement record. If a second Doppler measurement is made at some later point in time (FIG 6B), a second parabolic line of position 616b will be determined. The intersection 618 of the two lines of position 616a, 616b due to the two Doppler measurements will determine the position of the mobile unit 310 on the surface of the earth. While two Doppler measurements are indicated here, only one is necessary for use in the geolocation process of the present invention.

Doppler cone 610 is produced by measuring the Doppler shift of the received signal. In a transponder implementation, there is a second, known Doppler shift in the transmission between the satellite 304 and the ground station 302. Since the position and velocity of the satellite 304 is known, this second Doppler shift is removed to produce the Doppler shift of the signal at the received satellite 304.

Combined Doppler and Range Measurements

Referring to FIG 7, which shows the combined range and Doppler measurements, two position estimates 701, 703 are generated where the Doppler cone 610 intersects the circular line of position 705 from the range measurement. The true position can be solved for in a number of ways, which will be described below.

The position of the mobile unit 310 can be determined with only one combined measurement of Doppler and range. Assuming that the transceiver unit 310 is on the surface 503 of the earth, the Doppler cone 610 and range sphere 501

will intersect at two possible transceiver unit positions 701, 703 on the earth's surface. The intersection of the frequency of arrival curve with the time of arrival circle provides a two position solution to the location determination problem. One will be the true position and the other will be an image position. For a given satellite pass and mobile unit-to-satellite geometry these two positions will be at the same orthogonal distance from the satellite ground track where the range rate (hence Doppler shift) will be zero at the time of closest approach. One of these positions resides to the right of the ground track and the other resides to the left of the ground track. The ground track represents the axis of Doppler symmetry which is offset from the true satellite ground track by the earth's rotation. In the absence of earth's rotation, the two solutions would be indistinguishable. However, the inclusion of earth's rotation results in an altered Doppler characteristic which permits ambiguity resolution. If two or more satellite passes of data are available, this ambiguity is resolved simply from geometric considerations Also, position ambiguity will be resolved by knowing which satellite ID number and which beam footprint cell ID number 204-232 the mobile unit 310 is in, as previously discussed. Using the cell ID location parameter in the measurement, the ambiguity can be resolved.

Referring to FIG 2, a low Earth orbiting satellite beam footprint 200 is shown with a number of spot beams 202. When a position measurement is made, the intersection of a spot beam 202 with the range and Doppler lines of positions in many cases will generate a unique position solution. Thus, the true position can be resolved from the false position estimates. Other techniques for resolving the two position solutions range from the simple approach of knowing the last reported position, to more sophisticated approaches such as including the affect of Earth orbit rotation on the position solutions. The latter technique is currently in use in the Search and Rescue Satellite System (SARSAT), and in the Argos environmental research satellite tracking system.

Geolocation Method

We now turn to FIG 8, which depicts the method of the present invention 800. The method of the present invention includes four main parts. First, the

position of the reference transceiver is determined using two measurements: (1) the range to the reference transceiver via the transceiver response time (803); and (2) the angle of arrival of the reference transceiver via the Doppler shift measurement (805). After the two measurements are made, the position is calculated (807).

Second, the Error Vector is generated by comparing the known position of the reference transceiver with the position determined in the first part (809).

Third, the position of the transceiver in the unknown location is estimated using the same two measurements, i.e., (1) the range to the reference transceiver via the transceiver response time (811); and (2) the angle of arrival of the reference transceiver via the Doppler shift measurement (813). The position estimate is the calculated for the transceiver in the unknown position (815).

Finally, the Error Vector is applied to the estimated position to obtain the final position of the transceiver in the unknown location (817).

Referring to FIG 9, the Error Correction vector 903 is depicted that is measured when the reference transceiver is interrogated is used to correct the position of mobile customer transceivers in the local area. The advantage of this technique is that by measuring the position of the reference transceiver simultaneously with the position of the mobile transceiver, any errors that are correlated between the two measurements are removed. Correlated errors include all systematic errors such as satellite position and velocity errors, ionospheric propagation delay errors, tropospheric propagation delay errors, and Earth surface elevation modeling errors.

To determine the error correction vector 903, first the position of the reference transceiver is measured. This is the "measured position" 905. Next, the difference between the measured position 905 and the known position 901 is determined, which represents the error correction vector 903. The error correction vector is then used to correct the position of the customer transceiver 310 based on the initial position estimate 911 to obtain the improved position estimate 907.

Turning to FIG 10, which depicts a representative map of possible reference transceiver locations in a representative five state area. Representative sites include

Washington. D.C. (4). Blacksburg. Virginia (3). Richmond. Virginia (2) and mid West Virginia (1).

Reduction of Errors

The accuracy of the geolocation technique of the present invention as described above may not be sufficient to locate the mobile unit 310 to the desired degree of accuracy in all cases. The various sources of location error are random errors that can be expressed through standard deviations or other statistical variance terms. Several more position calculations may be made before concluding that sufficient position accuracy has been achieved. Additional location measurements may be performed through repetition measurements and a given mobile unit 310 Thus, the location process may perform additional measurements in order to average the results. The averaging of location estimates determined from a plurality of location parameter sets reduces the inaccuracies associated with the position estimation and causes the location accuracy to improve.

After the position is determined as discussed above, an error ellipse is established for the averaged measurements taken up to a given point in time. This error ellipse is determined by the number of measurements averaged, the variance terms that characterize the location parameters, and the currently estimated position location. This error distribution is an ellipse centered around the estimated location. It is more circular and covers a relatively small area when the error is minimal. Where the error is greater, the ellipse's area increases (less circular) and its shape becomes more flattened.

The performance of geolocation measurement is based upon a unique combination of techniques for geolocation and the estimation of the geolocation errors associated with each technique. These position techniques and their respective errors are specified in terms of the satellite operational orbital dynamics and geometry, the measurement of signal-to-noise ratios and their accuracies, the position errors of the satellites 304 based upon the GPS errors from which the satellite ephemeris is derived, satellite platform and mobile unit synchronization models, and the methods of computing mobile unit geolocation (i.e., frequency of arrival and time

of arrival curves). The performance analysis consists of several distinct steps. These steps include development of models that reflect operational concepts and provides root mean square (RMS) error estimates, determination of sensitivities of error sources to location errors and parametric error analysis, selection of geometries and parameters to obtain the expected results of actual measurements, and perform calibration of the models to actual measured data.

A key benefit of this model is that actual geolocation processing algorithms are employed, while error sources are represented by statistical distributions. Calibrations for error analysis is performed by adjusting the error distributions and removing biases. Using differing geolocation techniques provides the mechanism for determining algorithm performance as a function of the operational scenario. This provides the RMS errors as well as the mobile unit location estimates. The RMS errors statistically match the distributions of the mobile unit locations. The error distribution can be adjusted and biases removed to adequately reflect the mobile unit RMS location error while properly modeling the individual error distributions. The relative contribution of each error source to the actual mobile unit location error can determined as a function of the time duration of the measurement.

The method for establishing mobile unit geolocation accuracy will combine the error factors from the various geolocation techniques. In the computations, the biases are removed and the resulting RMS errors are propagated throughout the algorithm. In the analysis all RMS errors for an estimate will be converted into orthogonal RMS errors. In combining mutually independent variables, the associated estimated and orthogonal RMS errors will be projected onto a common orthogonal coordinate system and the resulting estimate and RMS errors computed by using sum of estimated and square root of the sum of projected RMS errors squared along each axis.

The RMS for the absolute mobile unit geolocation error is obtained by combining mutually independent RMS errors for the absolute geolocation error in the single satellite estimates and the relative mobile unit geolocation RMS errors. The geolocations of the mobile unit 310 and the relative RMS errors are computed from the set of loci determined by the measured parameter, associated RMS measurement

errors. and the relative RMS location errors. Projecting all RMS parameter errors onto a common Euclidean coordinate system. the estimate of the mobile unit location is found by minimizing its weighted (by the product projections if RMS error) distance to each loci. The resulting RMS parameter error of the mobile unit location estimate in each coordinate is given by $N(\Sigma^{N}_{i=1} \sigma_i^{-1})^{-1}$, where N is the number of loci used and σ_i is the RMS parameter error along a coordinate at the estimated mobile unit location normal with its loci (i to N). Note that the RMS error weights used in the estimate and resulting RMS parameter error depend on the RMS error value of the measurement at the line normal to the loci through the estimate, and hence will account for range dependent contribution to the error. Since ambiguities may be present on which branch of a loci surface to use when computing the normal. the true mobile unit location will be used.

The locations where frequency of arrival curves intersect time of arrival curves at right angles will experience small errors in Doppler component and propagation duration measurements, resulting in small geographic location errors. These locations are found further away from where the satellite nadir direction intersects the surface of the earth. The more tangential the frequency of arrival curves are to an intersecting time of arrival circle, the greater the geolocation error which results from small measurement errors. Moreover, the error is typically greater in a direction perpendicular to the satellite ground track than in a direction parallel to the satellite ground track.

After the error ellipse is determined, a position accuracy parameter is obtained that is associated with the position location measurements. Position accuracies are typically specified as circular error probable (CEP), in which position accuracy is defined as a circle centered on a position measurement. The error definition such as the error ellipse is compared with the position accuracy such as the CEP. After this it is determined whether the error is less than the position accuracy. The error is less if a predetermined percentage of the area of the error ellipse fits within the CEP. Further refinement is needed unless the area of the error ellipse is sufficiently confined within the CEP. If the error is not less than the allowable error. the measurement process is instructed to perform another measurement. This

refinement will cause the area of the error ellipse to shrink. At some point, the error ellipse will shrink to a point where it is determined that the error is less than the position accuracy. At this point, the geolocation system requires no further refinement of the location of the mobile unit 310, the position is declared, and the process is terminated.

Summary

Because the present invention is independent of GPS, the bulk, power consumption and cost of a GPS receiver is unnecessary. Differential GPS requires that the GPS receiver have an additional reference signal that is received at each GPS receiver for that receiver to operate. By computing the position of the transceiver at the central satellite ground station, the transceiver of the present invention is kept simple, inexpensive and has no power consumption associated with processing an additional reference signal. Consequently, its battery life is extended relative to differential GPS receivers.

Furthermore, GPS requires that signals be simultaneously acquired from multiple satellites to calculate a position fix. The combined range and Doppler technique used in the present invention only requires communication with one non-geostationary orbiting satellite. Thus, in situations where only one satellite link is attainable, the combined range and Doppler technique produces a position estimate while GPS cannot.

WHAT IS CLAIMED IS.

1. A method for locating a mobile unit comprising the steps of:

a) obtaining a first curve on the earth on which the mobile unit may be located;

b) obtaining a second curve on the earth on which the mobile unit may be located;

c) determining a point of intersection of the two curves on the earth, said intersection point representing an estimate of the position of the mobile unit;

d) performing steps a) through c) for a reference unit to obtain an estimate of the position of the reference unit, wherein a location of the reference unit is known;

e) comparing the estimate of the position of the reference unit with the known position of the reference unit to obtain an error vector; and

f) applying the error vector to the estimate of the position of the mobile unit to obtain the location of the mobile unit.

2. The method according to claim 1, wherein the step a) of obtaining the first curve comprises the substeps of:

(i) determining a time of arrival of a signal from the mobile unit at a satellite;

(ii) calculating a sphere on which the mobile unit must lie from the time of arrival of the signal; and

(iii) obtaining the first curve from the intersection of the sphere with the earth.

3. The method according to claim 1, wherein the step b) of obtaining the second curve comprises the substeps of:

(i) determining an angle of arrival of a signal from the mobile unit at a satellite;

(ii) calculating a cone on which the mobile unit must lie from the angle of arrival of the signal; and

(iii) obtaining the second curve from the intersection of the cone with the earth.

4. A method of operating a geolocation system having at least one low earth orbiting satellite and having at least one mobile unit placed to communicate with said low earth orbiting satellite, said method comprising the steps of:

communicating between said low earth orbiting satellite and said mobile unit using said low earth orbiting satellite which transponds an electromagnetic signal from the mobile unit to a system ground station terminal without further processing the electromagnetic signal;

communicating between said low earth orbiting satellite and said mobile unit to obtain a set of geolocation parameters.

obtaining an approximate geolocation for the said mobile unit, said geolocation having an error associated therewith;

determining a geolocation accuracy for said approximate geolocation by communicating between the low earth orbiting satellite and a reference station; and

refining the approximate geolocation for the mobile unit using said geolocation accuracy.

5. The method according to claim 4, wherein the geolocation parameters are obtained from measuring a doppler shift in the signal between the low earth orbiting satellite and the mobile unit.

6. The method according to claim 4, wherein the geolocation parameters are obtained from measuring a time of arrival of the signal between the low earth orbiting satellite and the mobile unit.

7. The method according to claim 5, wherein the geolocation parameters are obtained from measuring a time of arrival of the signal between the low earth orbiting satellite and the mobile unit.

8. A method of operating a geolocation system using electromagnetic signals transmitted from a mobile unit on or near the surface of the Earth to a single satellite in a constellation of satellites disposed in known orbits about the Earth, said method capable of determining with precision a location of the mobile unit, the mobile unit and low earth orbiting satellites being capable of moving selectively relative to other mobile units and low earth orbiting satellites, said method comprising the steps of:

a) distributing a multiplicity of reference station transponders at fixed site surveyed points throughout a geographical area;

b) determining an approximate location of the mobile unit by measuring at a satellite ground station, a Doppler frequency shift component of a first plurality of geolocation parameters, a time of arrival component of the first plurality of geolocation parameters, and an angle of arrival component of the first plurality of geolocation parameters of the mobile unit transmitter signal;

c) determining an approximate location of at least one of the multiplicity of reference stations unit by measuring at the satellite ground station, a Doppler frequency shift component of a second plurality of geolocation parameters, a time of arrival component of the second plurality of geolocation parameters, and an angle of arrival component of the second plurality of geolocation parameters of the mobile unit transmitter signal;

d) comparing the approximate location of the at least one of the multiplicity of the reference stations and an a priori known accurate location the at least one of the multiplicity of reference stations to obtain a differential error vector; and

e) applying the differential error vector to the approximate location of the mobile unit from step b) to obtain an accurate position of the mobile unit.

9. The method according to claim 8, further comprising the step of:

f) instructing the mobile unit transmitter to transmit via one of the low earth orbiting satellites

10. The method according to claim 8, further comprising the step of determining a precise location of each of the multiplicity of reference stations by

determining an accurate latitude and longitude of each of the multiplicity of reference stations, and the step c) of determining the approximate location of the at least one of the multiplicity of reference stations includes determining an approximate latitude and longitude of said at least one of the multiplicity of reference stations.

11. The method according to claim 8, wherein said step d) of comparing further comprises taking a first difference between an accurate latitude and an approximate latitude to provide a differential latitude correction of a magnitude corresponding to said first difference and of a direction to north or south, and taking a second difference between an accurate longitude and an approximate longitude to provide a differential longitude correction of a magnitude corresponding to said second difference and of a direction to east or west.

12. The method according to claim 8, wherein said step e) of applying the differential error vector includes combining an approximate mobile unit latitude and said differential latitude correction to obtain a corrected mobile unit latitude and combining an approximate mobile unit longitude and said differential longitude correction to obtain a corrected mobile unit longitude.

13. The method according to claim 8, wherein the step e) of applying is carried out at a command center.

14. The method according to claim 8, further comprising the steps of receiving at the mobile unit a broadcast identification code and comparing the broadcast identification code with a stored identification code in the mobile unit.

15. A system for determining with a high degree of accuracy a location of a mobile unit based upon signals transmitted from a low earth orbiting satellite, which is disposed in a known orbit about the earth, the mobile unit being capable of moving selectively throughout a geographical area, said system comprising:

a) a command center;

b) a transmitter for transmitting geolocation information and other data from the command center to the mobile unit;

c) a receiver for receiving Doppler frequency shift, time of arrival, and angle of arrival data. and other data from the mobile unit via the plurality of low earth orbiting satellites to the command center; and

d) a measurement/geolocation/service processor residing in the command center, said processor determining a Doppler frequency shift component of a plurality of geolocation parameters, a time of arrival component of the plurality of geolocation parameters, an angle of arrival component of the plurality of geolocation parameters, and an approximate position of the mobile unit transmitter signal traveling between the mobile unit and the low earth orbiting satellite. wherein the command center includes a receiver for receiving differential data regarding a plurality of fixed reference stations and said approximate position of the mobile unit, and said processor determines based upon the approximate position of the mobile unit and known locations of the plurality of fixed reference stations a determined one of said plurality of fixed reference stations that is presently in view of the satellite as the mobile unit, and said processor combines the approximate position of the mobile unit and the differential data from the determined one differential station to provide an accurate position of the mobile unit.

16. An apparatus for locating a mobile unit comprising:

a) first means for obtaining a first curve on the earth on which the mobile unit may be located, and for obtaining a first curve on the earth on which a reference unit may be located;

b) second means for obtaining a second curve on the earth on which the mobile unit may be located, and for obtaining a second curve on the earth on which the reference unit may be located;

c) means for determining a first point of intersection on the earth of the first and second curves for the mobile unit, and a second point of intersection on the earth of the first and second curves of the reference unit, said first and second intersection

points representing an estimate of the position of the mobile unit and the reference unit, respectively;

d) means for comparing the estimate of the position of the reference unit with a known position of the reference unit to obtain an error vector; and

e) means for applying the error vector to the estimate of the position of the mobile unit to obtain the location of the mobile unit.

17. The apparatus according to claim 16, wherein the first means for obtaining further comprises:

means for determining a time of arrival of a signal from the mobile unit and a signal from the reference unit at a satellite;

means for calculating a shere on which the mobile unit must lie from the time of arrival of the signal from the reference unit and for calculating a shere on which the reference unit must lie from the time of arrival of the signal from the reference unit; and

means for obtaining the first curve for the mobile unit from the intersection of the sphere for the mobile unit with the earth, and for obtaining the first curve for the reference unit from the intersection of the sphere for the reference unit with the earth.

18. The method according to claim 1, wherein the second means for obtaining further comprises:

means for determining an angle of arrival of a signal from the mobile unit at a satellite, and for determining an angle of arrival of a signal from the reference unit at the satellite;

means for calculating a cone on which the mobile unit must lie from the angle of arrival of the signal from the mobile unit, and for calculating a cone on which the reference unit must lie from the angle of arrival of the signal from the reference unit; and

means for obtaining the second curve for the mobile unit from the intersection of the cone for the mobile unit with the earth, and for obtaining the second curve for

the reference unit from the intersection of the cone for the reference unit with the earth.

19. An apparatus for operating a geolocation system having at least one low earth orbiting satellite and having at least one mobile unit placed to communicate with said low earth orbiting satellite, said apparatus comprising:

means for communicating between said low earth orbiting satellite and said mobile unit using said low earth orbiting satellite which transponds an electromagnetic signal from the mobile unit to a system ground station terminal without further processing the electromagnetic signal;

means for communicating between said low earth orbiting satellite and said mobile unit to obtain a set of geolocation parameters;

means for obtaining an approximate geolocation for the said mobile unit, said geolocation having an error associated therewith;

means for determining a geolocation accuracy for said approximate geolocation by communicating between the low earth orbiting satellite and a reference station; and

means for refining the approximate geolocation for the mobile unit using said geolocation accuracy.

20. The apparatus according to claim 19, wherein the geolocation parameters are obtained from measuring a doppler shift in the signal between the low earth orbiting satellite and the mobile unit.

21. The apparatus according to claim 19, wherein the geolocation parameters are obtained from measuring a time of arrival of the signal between the low earth orbiting satellite and the mobile unit.

22. The apparatus according to claim 21, wherein the geolocation parameters are obtained from measuring a time of arrival of the signal between the low earth orbiting satellite and the mobile unit.

23. A geolocation system using electromagnetic signals transmitted from a mobile unit on or near the surface of the Earth to a single satellite in a constellation of satellites disposed in known orbits about the Earth, said method capable of determining with precision a location of the mobile unit, the mobile unit and low earth orbiting satellites being capable of moving selectively relative to other mobile units and low earth orbiting satellites, said method comprising the steps of:

a) a multiplicity of reference station transponders distributed at fixed site surveyed points throughout a geographical area; and

b) a processor: (1) determining an approximate location of the mobile unit by measuring at a satellite ground station, a Doppler frequency shift component of a first plurality of geolocation parameters, a time of arrival component of the first plurality of geolocation parameters, and an angle of arrival component of the first plurality of geolocation parameters of the mobile unit transmitter signal, (2) determining an approximate location of at least one of the multiplicity of reference stations unit by measuring at the satellite ground station, a Doppler frequency shift component of a second plurality of geolocation parameters, a time of arrival component of the second plurality of geolocation parameters, and an angle of arrival component of the second plurality of geolocation parameters of the mobile unit transmitter signal, and (3) comparing the approximate location of the at least one of the multiplicity of the reference stations and an a priori known accurate location the at least one of the multiplicity of reference stations to obtain a differential error vector, and applying the differential error vector to the approximate location of the mobile unit from (1) to obtain an accurate position of the mobile unit.

24. A method for geolocating a device comprising the steps of determining an error vector representing a difference between a known location of a fixed reference station and a measured location, and applying that error vector to a measured location of the device.

25. A method for locating a mobile unit includes the steps of determining the location of a reference unit. calculating an error vector that represents the difference between the actual known position and the measured position. estimating the position of the mobile unit using the same technique used to measure the location of the reference unit, and applying the error vector to the estimate position of the mobile unit to determine the final position of the mobile unit.

200 SATELLITE FOOTPRINT

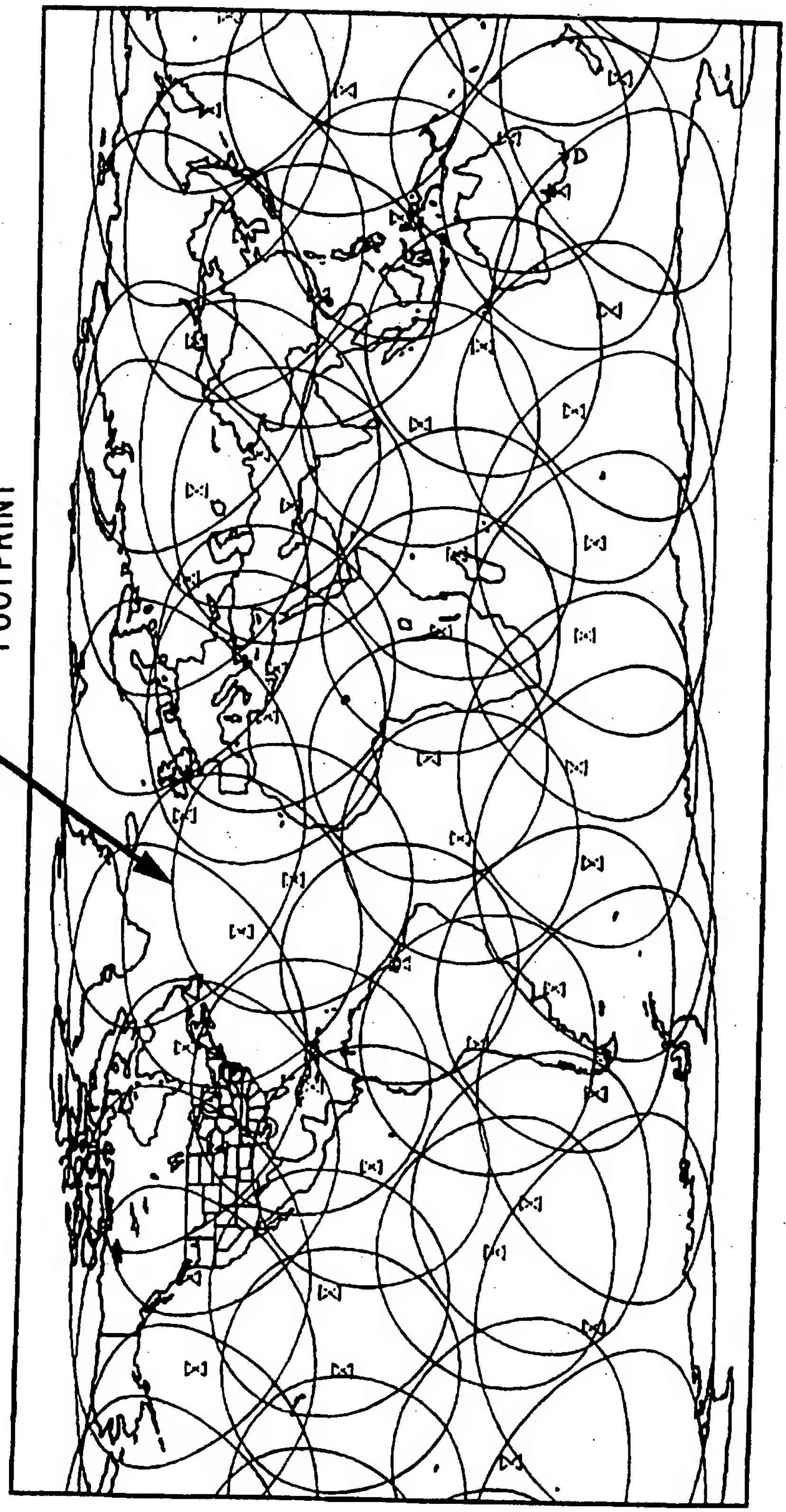

FIG. 1

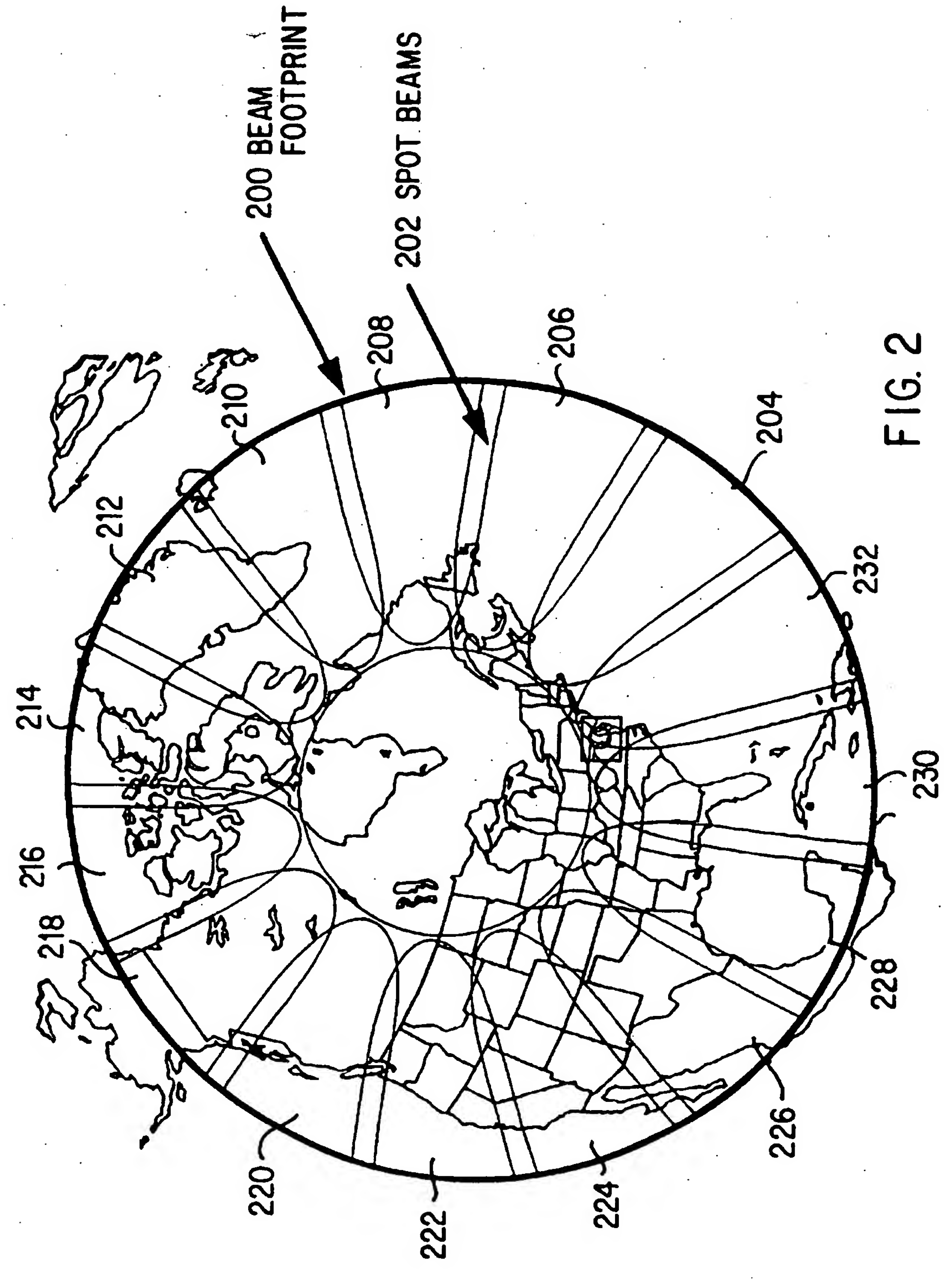
200 BEAM FOOTPRINT
202 SPOT BEAMS
204
206
208
210
212
214
216
218
220
222
224
226
228
230
232

FIG. 2

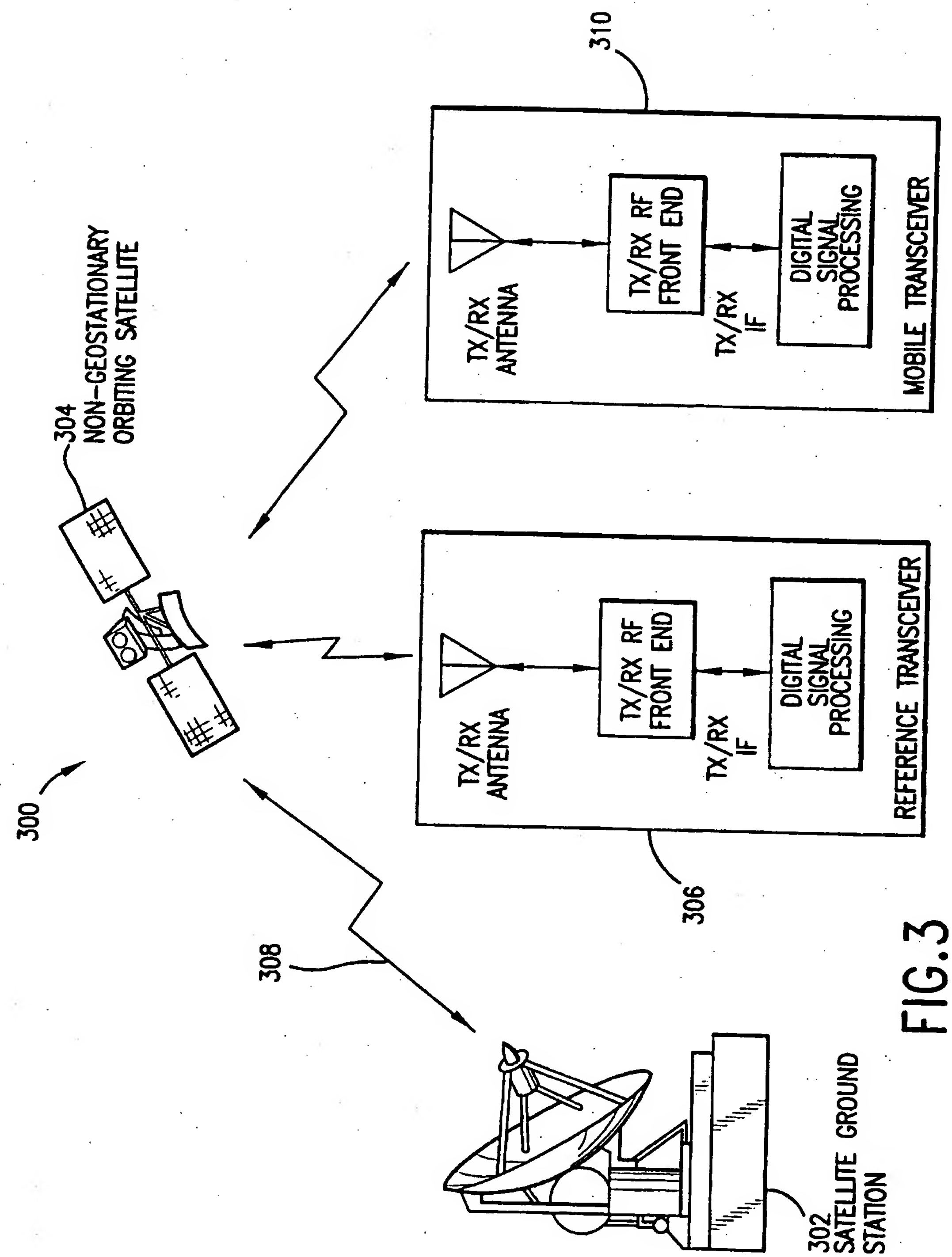
300
304
NON-GEOSTATIONARY ORBITING SATELLITE
310
TX/RX ANTENNA
TX/RX RF FRONT END
TX/RX IF
DIGITAL SIGNAL PROCESSING
MOBILE TRANSCEIVER
TX/RX ANTENNA
TX/RX RF FRONT END
TX/RX IF
DIGITAL SIGNAL PROCESSING
REFERENCE TRANSCEIVER
306
308
302
SATELLITE GROUND STATION

FIG.3

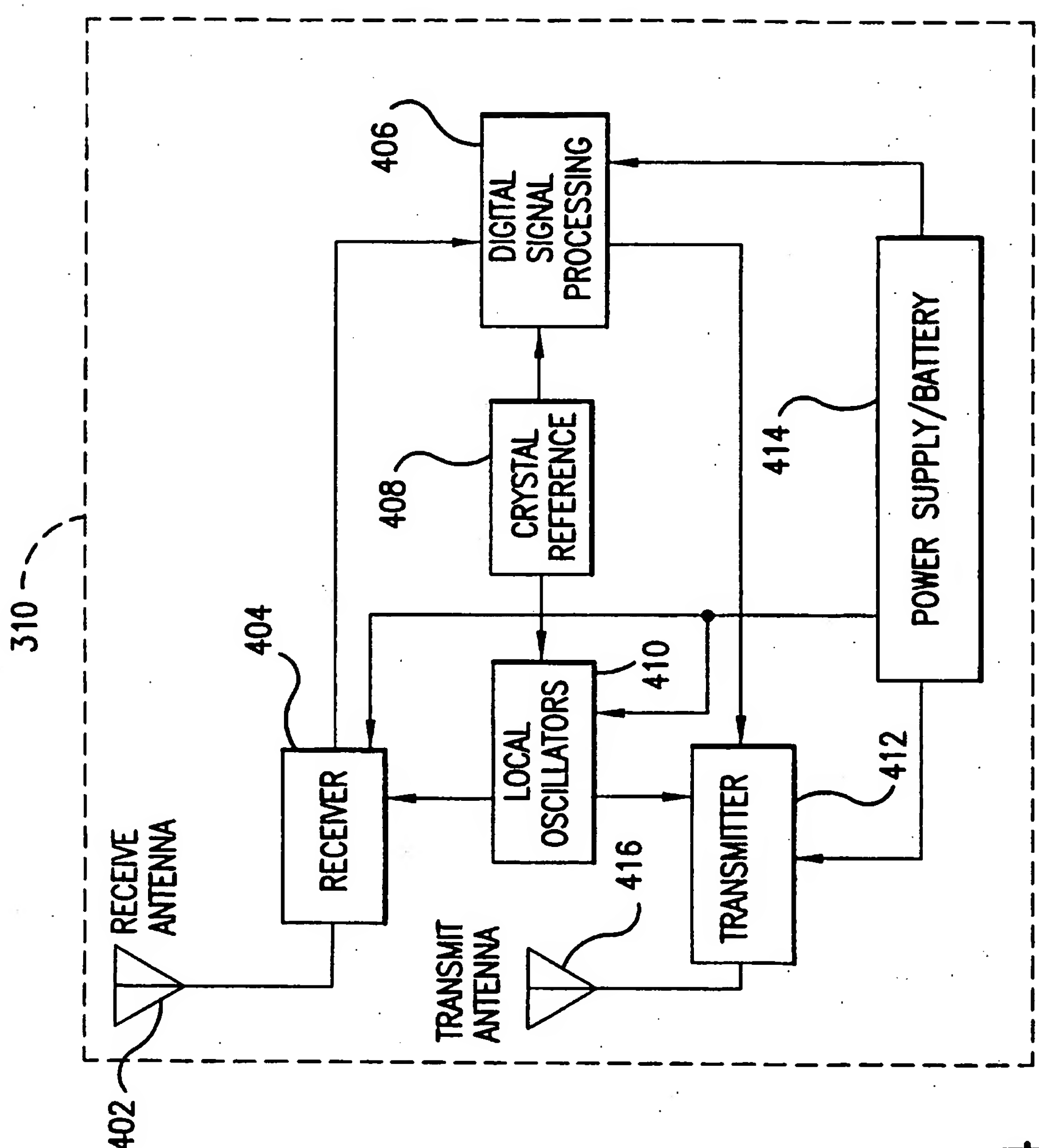
310
RECEIVE ANTENNA
402
RECEIVER
404
DIGITAL SIGNAL PROCESSING
406
CRYSTAL REFERENCE
408
LOCAL OSCILLATORS
410
TRANSMITTER
412
POWER SUPPLY/BATTERY
414
TRANSMIT ANTENNA
416

FIG.4

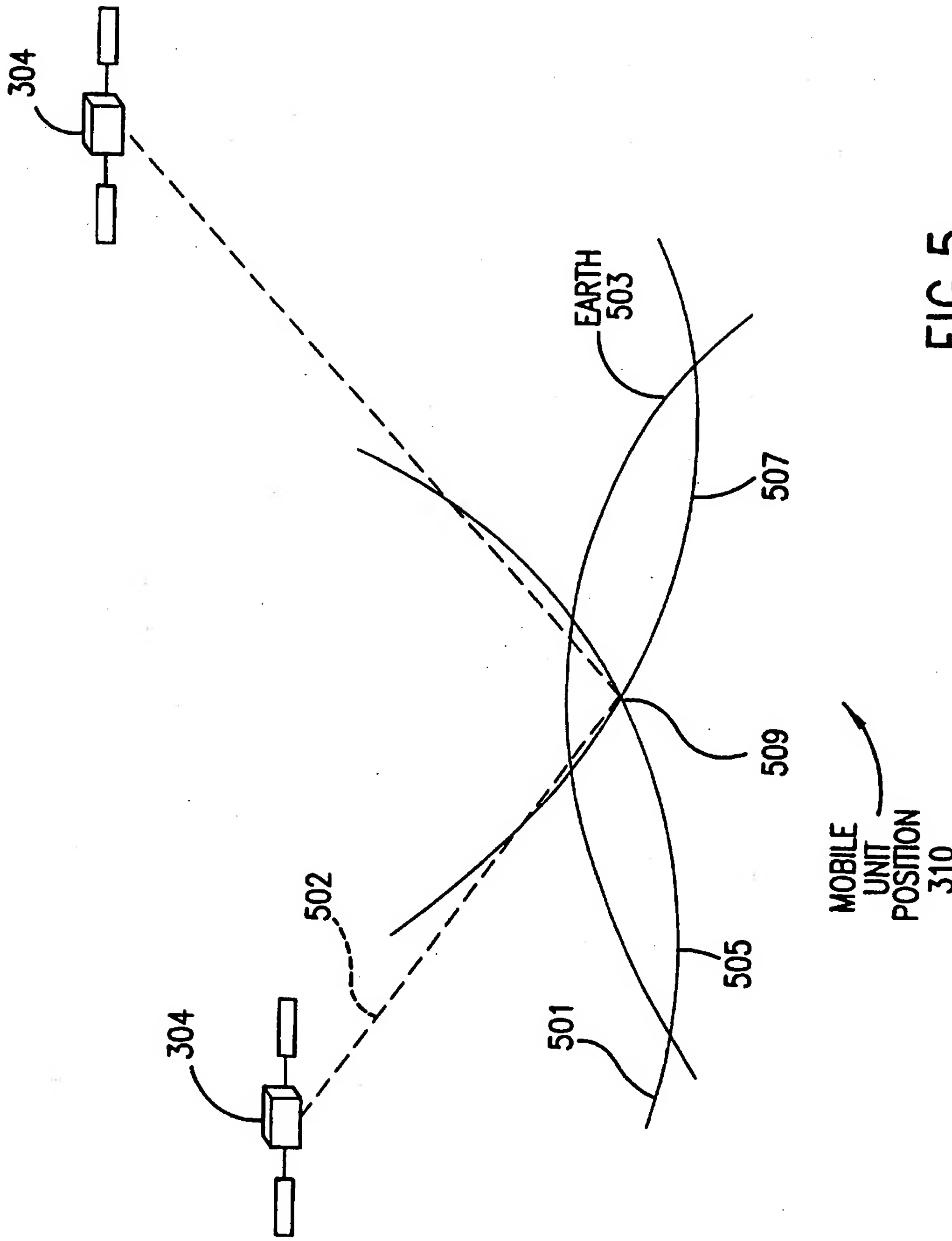
304
EARTH 503
507
509
MOBILE UNIT POSITION 310
502
505
501
304

FIG.5

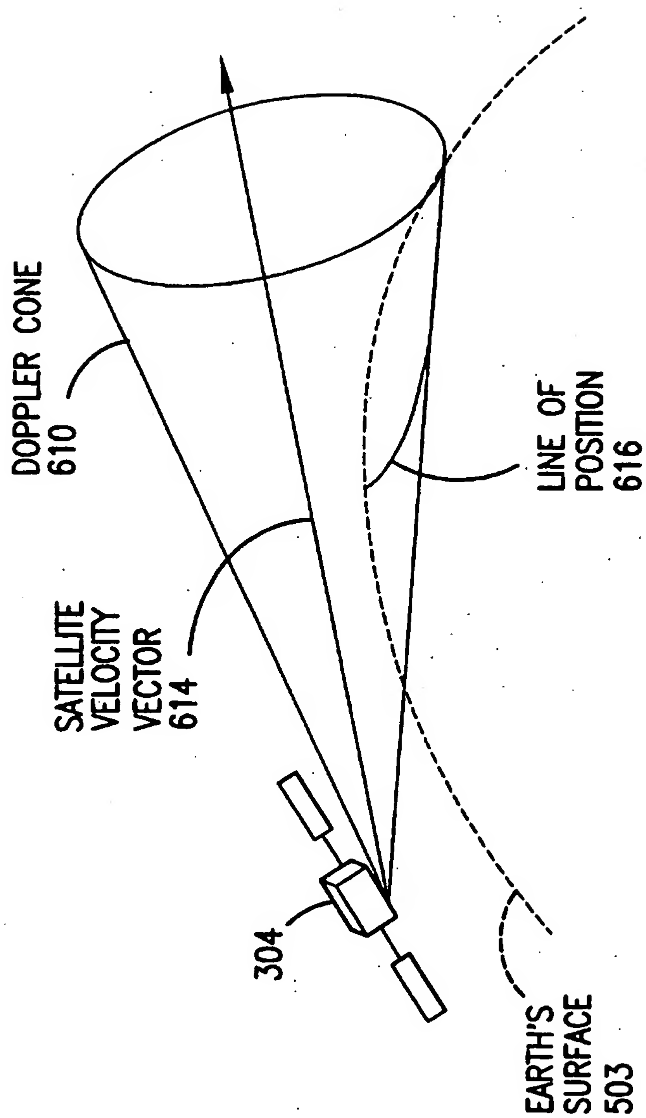
DOPPLER CONE
610
SATELLITE
VELOCITY
VECTOR
614
LINE OF
POSITION
616
304
EARTH'S
SURFACE
503

FIG.6A

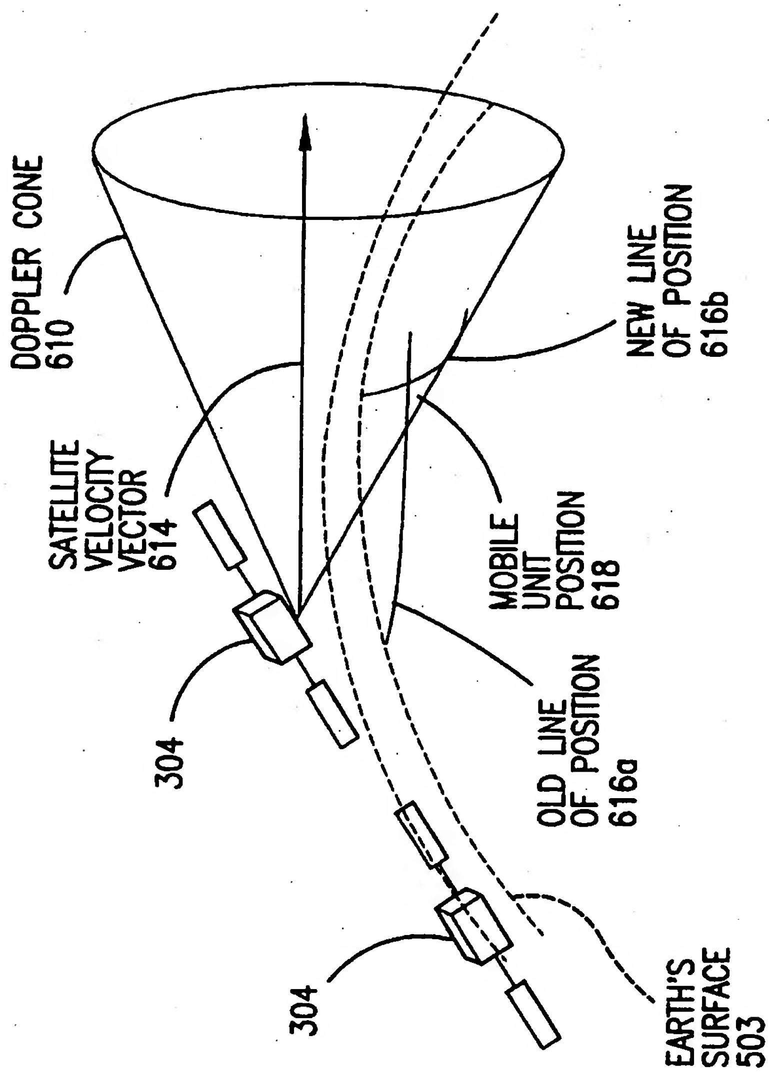
DOPPLER CONE
610
SATELLITE VELOCITY VECTOR
614
304
NEW LINE OF POSITION
616b
MOBILE UNIT POSITION
618
OLD LINE OF POSITION
616a
304
EARTH'S SURFACE
503

FIG.6B

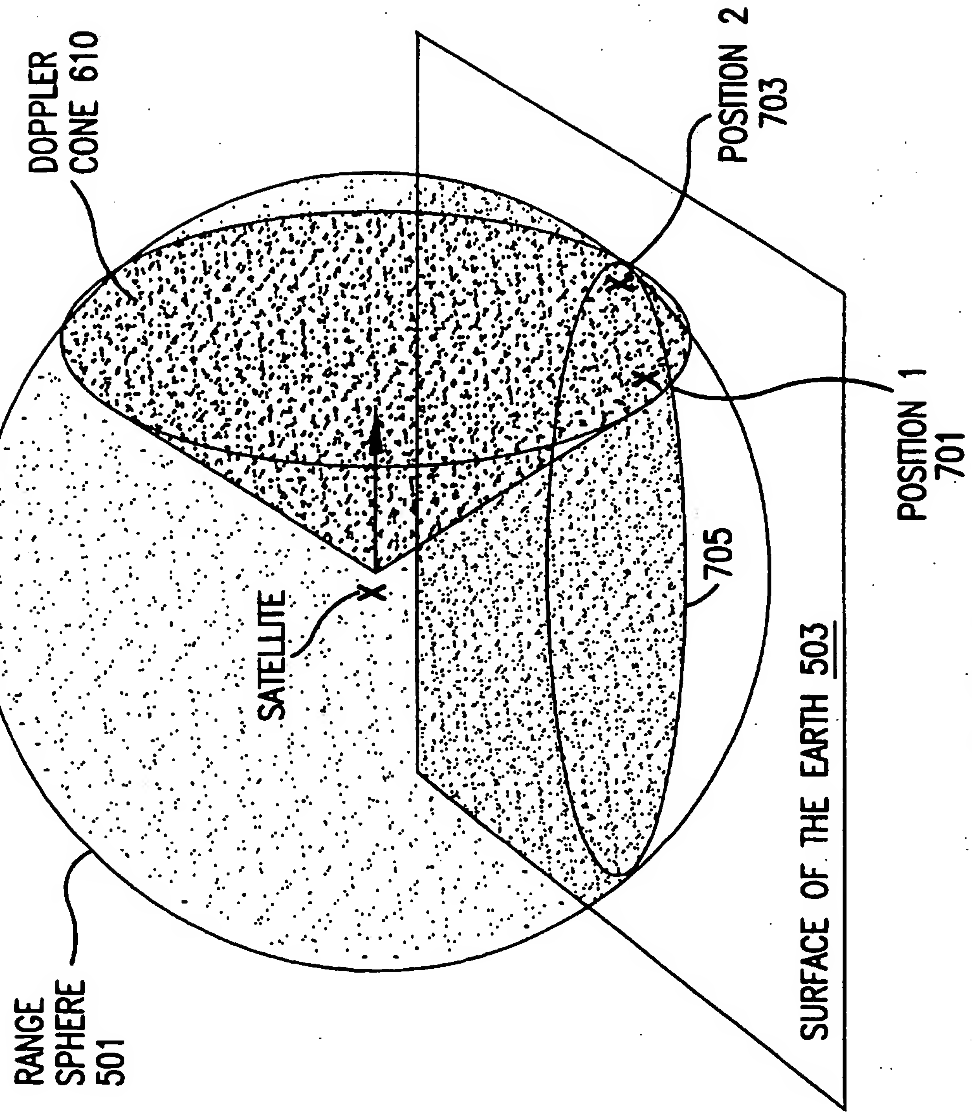
DOPPLER
CONE 610
POSITION 2
703
POSITION 1
701
705
SATELLITE
SURFACE OF THE EARTH 503
RANGE
SPHERE
501

FIG.7

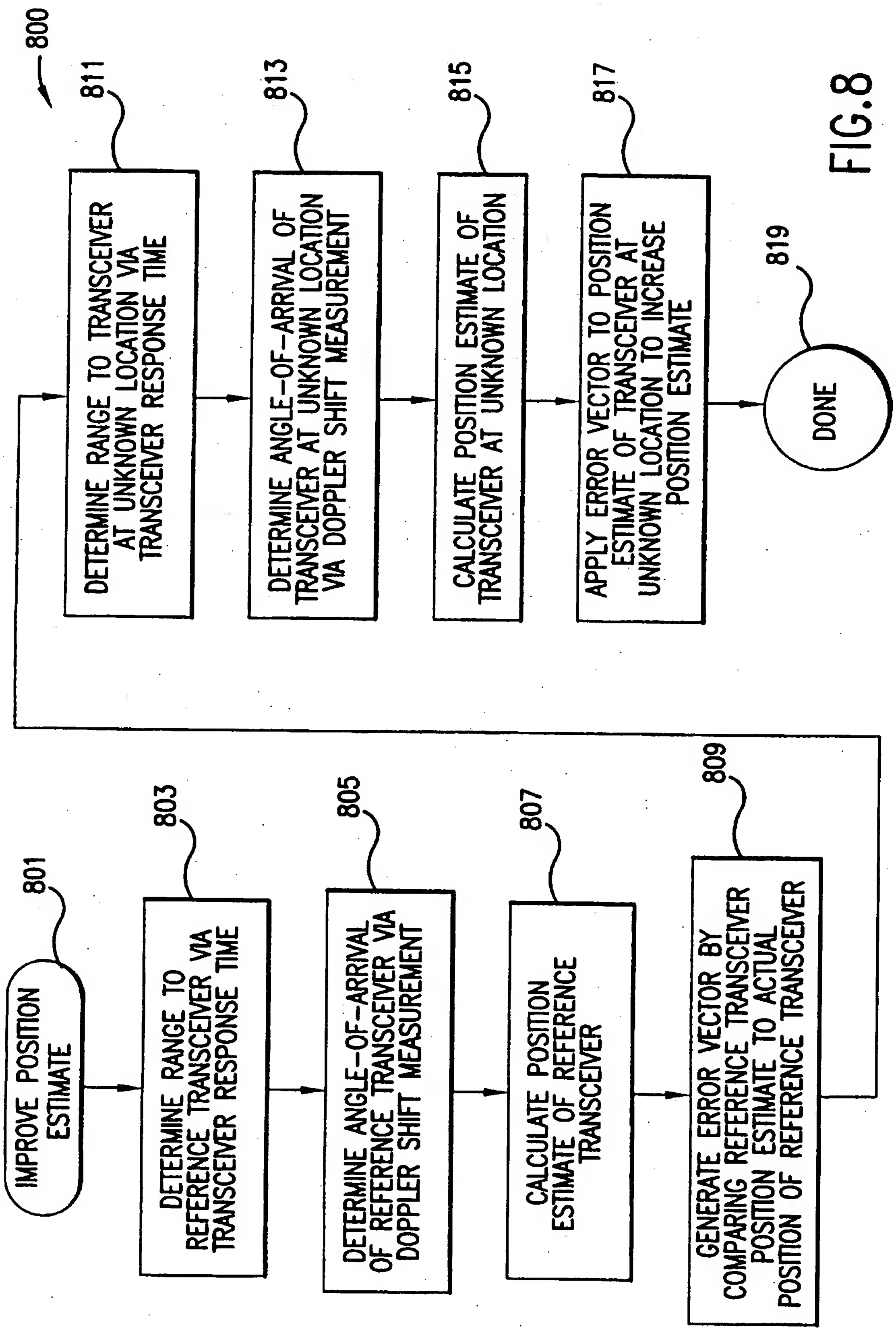
800
801
IMPROVE POSITION ESTIMATE
803
DETERMINE RANGE TO REFERENCE TRANSCEIVER VIA TRANSCEIVER RESPONSE TIME
805
DETERMINE ANGLE-OF-ARRIVAL OF REFERENCE TRANSCEIVER VIA DOPPLER SHIFT MEASUREMENT
807
CALCULATE POSITION ESTIMATE OF REFERENCE TRANSCEIVER
809
GENERATE ERROR VECTOR BY COMPARING REFERENCE TRANSCEIVER POSITION ESTIMATE TO ACTUAL POSITION OF REFERENCE TRANSCEIVER
811
DETERMINE RANGE TO TRANSCEIVER AT UNKNOWN LOCATION VIA TRANSCEIVER RESPONSE TIME
813
DETERMINE ANGLE-OF-ARRIVAL OF TRANSCEIVER AT UNKNOWN LOCATION VIA DOPPLER SHIFT MEASUREMENT
815
CALCULATE POSITION ESTIMATE OF TRANSCEIVER AT UNKNOWN LOCATION
817
APPLY ERROR VECTOR TO POSITION ESTIMATE OF TRANSCEIVER AT UNKNOWN LOCATION TO INCREASE POSITION ESTIMATE
819
DONE

FIG.8

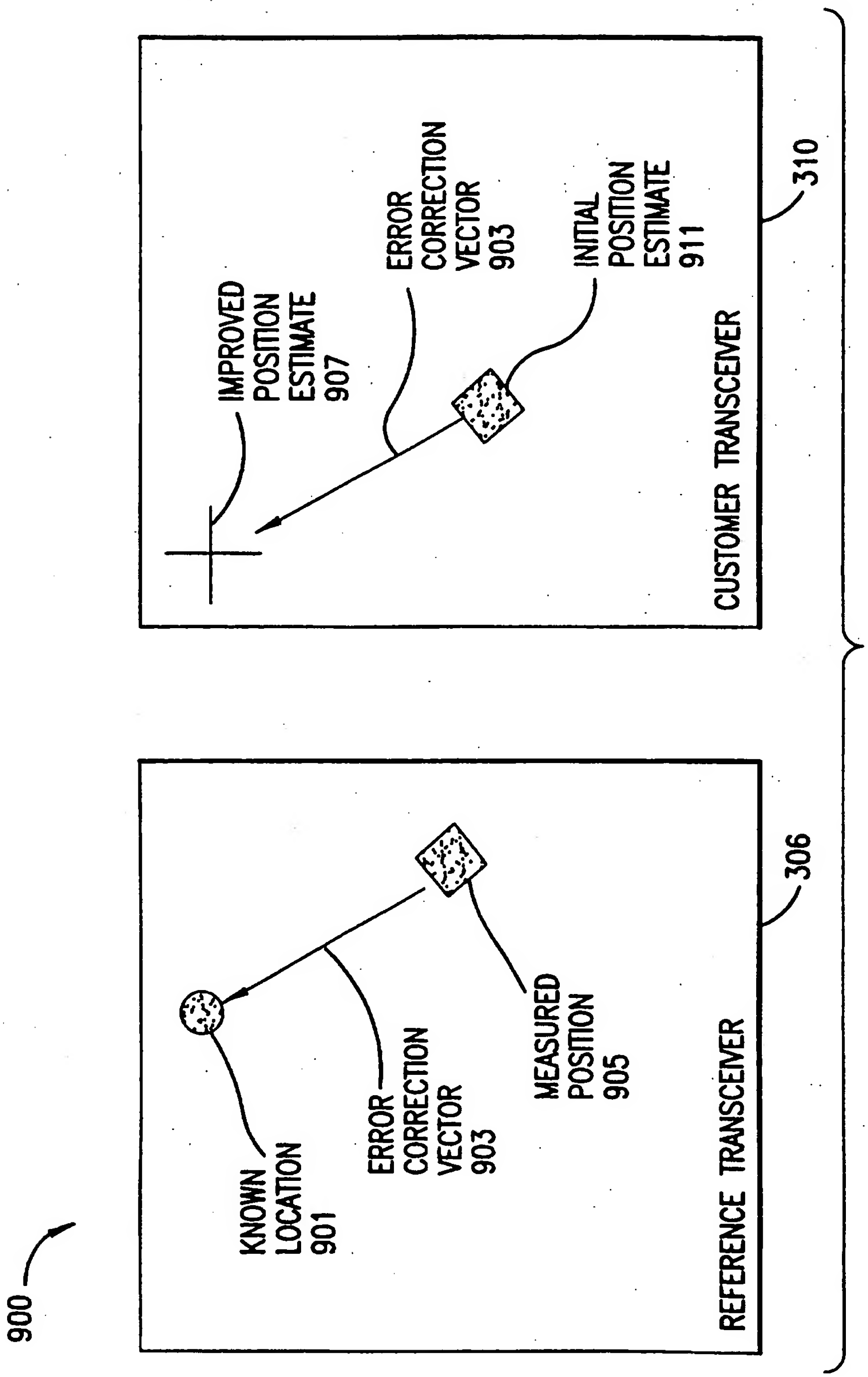
900
KNOWN LOCATION 901
ERROR CORRECTION VECTOR 903
MEASURED POSITION 905
REFERENCE TRANSCEIVER
306
IMPROVED POSITION ESTIMATE 907
ERROR CORRECTION VECTOR 903
INITIAL POSITION ESTIMATE 911
CUSTOMER TRANSCEIVER
310

FIG.9

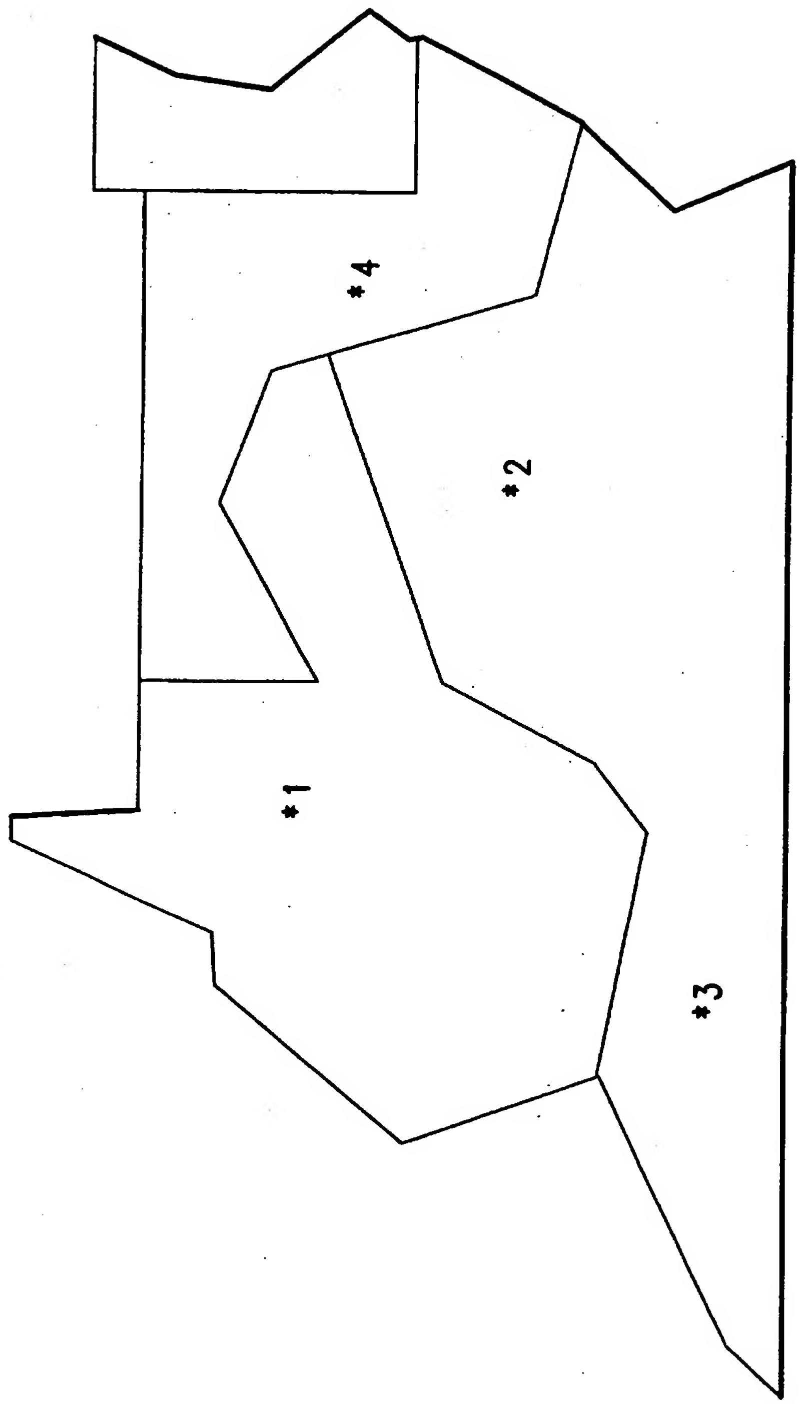

FIG.10